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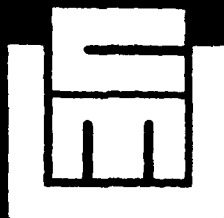
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INTEGRATED OPTIC SIGNAL PROCESSORS
FOR WIDEBAND RADAR SYSTEMS

ANNUAL TECHNICAL REPORT I

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Ballistic Missile Defense Advanced
Technology Center

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July 15, 1977 - July 14, 1978

Prepared By

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Research effort for the first program year was placed on the utilization of wideband guided-wave (thin-film) acoustooptic deflectors for real-time pulse compression and convolution of wideband RF signals. For this purpose a very wideband deflector in a Y-cut LiNbO ₃ Ti-diffused waveguide having a measured bandwidth of 500 MHz was designed and fabricated. This deflector employs a three-element tilted-array transducer with the center frequencies of (Continued on Opposite Side)		

275, 432 and 648 MHz, and has a measured deflector bandwidth of 500 MHz. This bandwidth represents the largest that has been achieved thus far.

With regard to the first subarea on pulse compression, we have for the first time succeeded in a guided-wave acoustooptic pulse compression experiment. We have obtained a compression ratio as large as 300 and a bandwidth of 120 MHz. We have also measured a number of basic parameters and achieved a good agreement between theory and experiment. As to the second subarea on convolution, we have initiated a detailed theoretical study aiming at determining the ultimate performance figures of the convolvers such as bandwidth, time-bandwidth product, and dynamic-range. This theoretical study is progressing at a good speed.

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INTEGRATED OPTIC SIGNAL PROCESSORS
FOR WIDEBAND RADAR SYSTEMS

CONTRACT DAS G 60-77-C-0136

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ANNUAL TECHNICAL REPORT I

I. INTRODUCTION

A. Integrated Optics Technology

Integrated Optics is an emerging technology that has been actively pursued in recent years.⁽¹⁾ The ultimate objective of integrated optics is to realize miniature optical components such as light sources, modulators, switches, deflectors, lenses, prisms, and detectors in a substrate to perform various useful functions. Like the existing integrated electronics in which a large number of active and passive components such as transistors, diodes, resistors and capacitors are packed in a small area semiconductor chip, the integrated optics, when fully developed, are expected to have many advantages over the existing bulk optical systems. Some of the advantages of the miniature components over their bulk counterparts are smaller size and lighter weight, wider bandwidth, lesser electrical drive power requirement, greater signal accessibility and integratability. The miniature components are also expected to possess advantages in stability, reliability, ruggedness and ultimate cost.⁽¹⁾

It has now been well recognized that the most immediate and important applications of integrated optics lie in the areas of wideband multichannel communications (for both military and civilian) and signal processings (for military hardwares such as radars).⁽²⁾ With regard to communications, a number of first-generation low data rate laboratory and field test systems have been built and their performance have demonstrated their potential. With regard to signal processings, the research and development efforts have just begun.^(3,4)

B. Guided-Wave (Thin-Film) Acoustooptics

An acoustic (sound) wave can induce a significant change in the refractive index of a material and thus create an optical grating to diffract a light beam. This sound-light interaction, commonly called the acoustooptic interaction, was discovered as far back as 1932 and was studied in many liquids up to early 1950's. These earlier studies employed incoherent light sources and bulk acoustic waves of relatively low frequency. Since 1965 a great deal of R and D work on this subject have been carried out in a variety of solid materials using coherent light sources and bulk acoustic waves of much higher frequency. This surge of activity was mainly due to the advent of the lasers and the advancement in the bulk acoustic wave transducer technology. Various types of bulk-wave acoustooptic devices such as the modulators, scanners, switches and filters for a laser beam as well as the data processors for radio frequency signals have now become available commercially and are being deployed in a variety of applications.

Recent research on acoustooptic interaction involves a new form of interaction configuration in which both the coherent light wave and the acoustic wave are guided in a planar substrate. A wave is said to be guided if its energy is confined in a thin layer beneath the substrate. The extension of research on acoustooptic interaction to the guided-wave (thin-film) form described above was motivated by the recent emergence in surface acoustic waves technology* and the integrated optics technology described earlier. A surface acoustic wave (SAW) can be generated by applying a radio frequency signal across an interdigital finger electrode pattern deposited on a piezoelectric substrate. Surface acoustic waves propagate on a material substrate and has most of its energy contained in a thin layer right beneath the surface. As indicated earlier, the integrated optic systems when fully developed are expected to have a number of advantages over the existing bulk optical systems. Specifically, the thin-film acoustooptic devices, in comparison to their bulk-wave counterparts, possess inherent advantages of requiring less electric drive power, being smaller, lighter in weight, less susceptible to environmental effects, and more integratable, and thus potentially less costly.

C-MU has been actively engaged in research on new guided-wave acoustooptic and electrooptic devices with applications to future wideband multichannel integrated/fiber optic communication and signal processing systems. Through the supports of various government agencies a number of novel concepts and devices have been discovered and developed. For example, several techniques for wideband guided-wave light beam deflection and switching have been developed under the supports of

*R.M. White, "Surface Elastic Waves," Proc. IEEE, 58, 1238 (August 1970).

the NSF and the ONR.⁽⁵⁾ For example, a composite bandwidth as large as 500 MHz has been demonstrated in a device which was fabricated in a Y-cut LiNbO_3 waveguide.⁽⁶⁾ To provide an appreciation of this bandwidth we note that a 500 MHz bandwidth acoustooptic light beam scanner is capable of deflecting a light beam of 1 cm aperture into 1,400 resolvable beam diameters, requiring a switching time of 2.4×10^{-6} sec between any two resolvable beam diameters.

Development of these wideband techniques has made possible to design and fabricate high-performance thin-film acoustooptic devices, and has thus paved the way for the realization of a variety of potential applications.⁽⁶⁾ These potential applications include high-resolution light beam deflectors, spectrum analyzers, convolvers, pulse compressors, correlators, multiplexers/demultiplexers, and tunable optical filters. For example, a number of military and civilian laboratories are currently using wideband thin-film acoustooptic deflectors to develop an integrated acoustooptic spectrum analyzer for data processing of very wideband radio frequency signals.⁽⁴⁻⁷⁾ A spectrum analyzer is used to measure the frequency components as well as their relative strength contained in a complex radio frequency signal.

II. RESEARCH OBJECTIVES

The general objective of this long-term research program is to explore the potential of integrated optic technology with application to wideband radar systems. Specific tasks of the research program are: (1) to advance the performance characteristics such as bandwidth, time-bandwidth product and dynamic range of a number of novel thin-film acoustooptic and electrooptic devices, (2) to create a group of new devices and to study the underlying interaction mechanisms, and (3) to explore a number of thin-film optical signal processors using the above devices, and to determine their ultimate capability. The ultimate objective of the research program is to study and develop high-performance integrated optic processors for the processing of wideband radar signals.

Although six subareas of research were suggested in the original proposal it was agreed that for the first year the research would be carried out for the first two subareas, namely, acoustooptic pulse compressors and acoustooptic convolvers. Some very encouraging progress on these two subareas has been achieved during the past year.

III. GUIDED-WAVE ACOUSTOOPTIC PULSE COMPRESSORS

A. Technical Discussion

One of the commonly used RF pulses which can provide long range and good range resolution in radar is the so called linear FM pulse (chirp pulse) in which

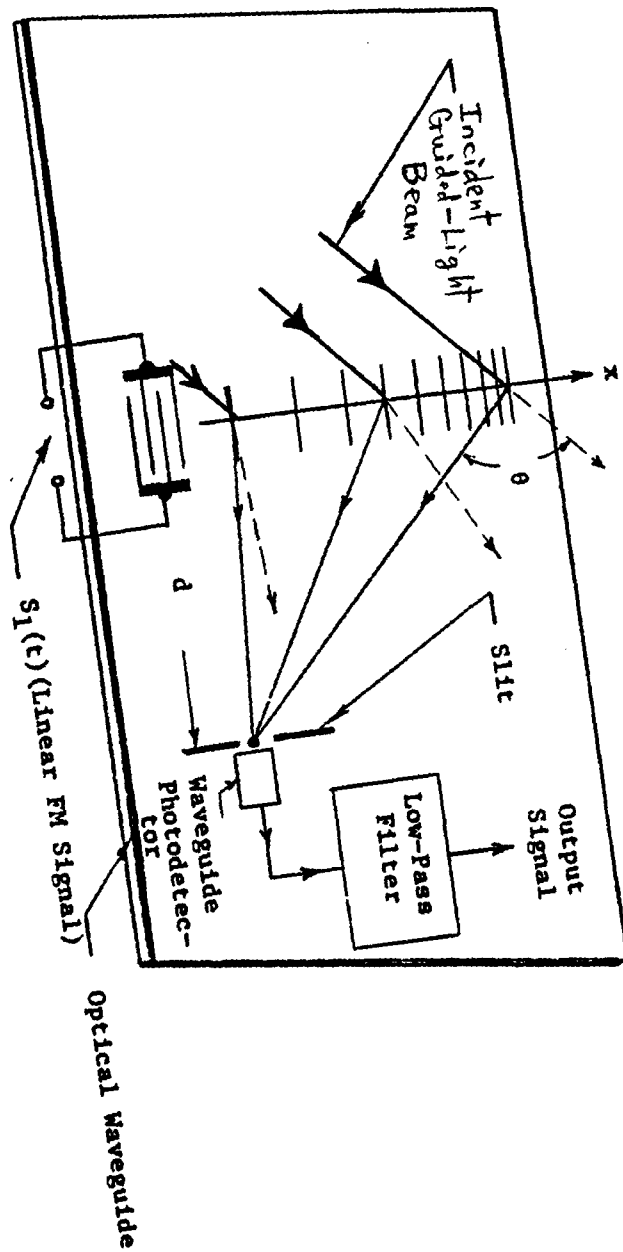
the carrier frequency varies linearly within the pulse. By means of a signal processing technique referred to as "radar pulse compression" at the receiver, the feeble radar echoes may be made sharp and strong. Thus, the characteristics of a radar pulse compressor are the width and the intensity of the output compressed pulse. The pulse width Δt is approximately equal to $1/B$, where B is the bandwidth of the chirp pulse. The pulse intensity is enhanced over that before pulse compression by a factor equal to TB , commonly called the compression ratio or time-bandwidth product, where T is the width of the chirp pulse.

The potential of real-time processing of radar chirp RF signals using coherent acoustooptical approaches have long been recognized.⁽⁸⁾ As a matter of fact, AO pulse compressors of various configurations using bulk-wave AO cells have been examined in recent years.^(8,9) These AO pulse compressors have been shown to be capable of processing a wide variety of signal codes and waveforms. The capacity of such bulk-wave AO pulse compressors is mainly limited by the bandwidth of the AO cells. In a guided-wave AO pulse compressor (See Fig. 1), a linear FM pulse is used to generate the surface acoustic waves (SAWs). The SAWs in turn create an optical grating in the optical waveguide which acts as a moving Fresnel zone lens. Thus, the Bragg-diffracted light resulting from a collimated incident light beam will be brought to a focus, and the focal spot sweeps in the focal plane at the acoustic wave velocity. A high-speed photodetector with a sufficiently narrow aperture will register an intense, compressed optical pulse. Since the light energy from the entire aperture of T seconds in length produces a current pulse of length Δt , it is clear that pulse compression has been accomplished with a compression ratio of $T/\Delta t$.

B. Major Accomplishments

During the past year both theoretical and experimental studies were initiated and pursued. Much progress has been achieved. On the theoretical study, a calculation on Bragg diffraction of a plane incident guided-light beam from a surface acoustic wave of a linearly-varying periodicity (See Fig. 2) was carried out. This type of surface acoustic wave represents that generated by a linear-FM or chirp drive signal. As indicated in the above technical discussion, the Bragg-diffracted light is brought to a focus and scans at the acoustic wave velocity. The key parameters of the Bragg-diffracted light are:

Fig. 1
Thin-Film Acoustooptic Pulse Compressor Using
One Bragg Cell



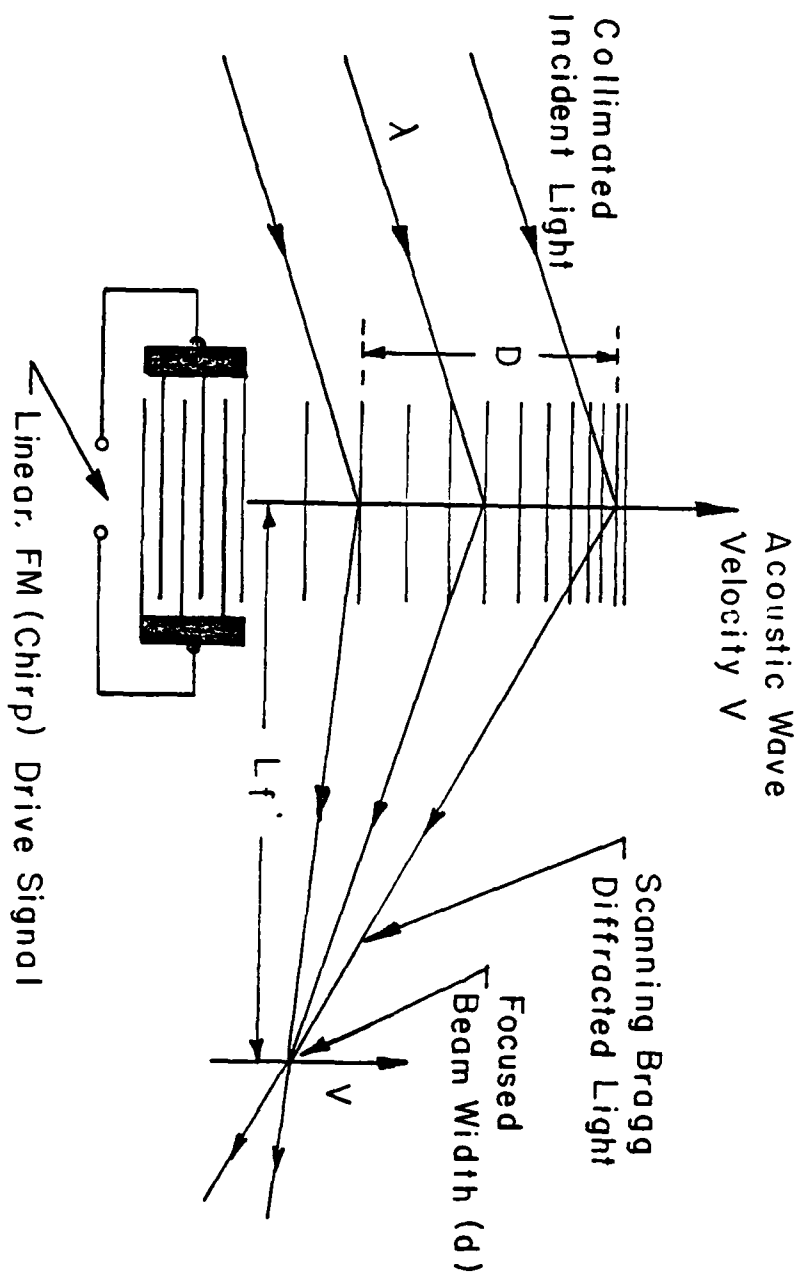


FIG. 2 BRAGG-DIFFRACTION OF A COLLIMATED GUIDED-LIGHT FROM A SURFACE ACOUSTIC WAVE GENERATED BY A CHIRP SIGNAL

$$\text{Focal Length } L_f = \frac{DV}{\lambda \Delta f} = \left(\frac{V^2}{\lambda}\right) \left(\frac{\tau}{\Delta f}\right) \quad (1)$$

$$\text{Focused Beam Width } d = \frac{V}{\Delta f} \quad (2)$$

$$\text{Scanning Velocity} = V \quad (3)$$

$$\text{Where } \begin{cases} \Delta f = \text{Bandwidth Of Linear FM Drive Within The} \\ \quad \text{Light Beam Aperture } D \\ \tau = D/V = \text{Acoustic Transit Time Across Aperture } D \end{cases}$$

This Bragg-diffracted light may be utilized in two basic applications, namely, optical pulse compression⁽¹⁰⁾ and very high-speed light beam scanning.⁽³⁾ In the first application which is the concern of this research, it is clear that the width of the compressed optical pulse, Δt , is given by the following relation:

$$\Delta t \approx \frac{d}{V} \approx \frac{1}{\Delta f} \quad (4)$$

Finally, the compression ratio, R , which is defined as the ratio of the width of the chirp pulse and the compressed optical pulse width is given as follows:

$$R \approx \frac{\tau}{\Delta t} \approx \tau \Delta f \quad (5)$$

Eq. (5) states that the compression ratio or the processing gain of the acousto-optic pulse compressor is equal to the time-bandwidth product of the acoustooptic deflector.

With regard to the second application, it can be shown that the maximum scanning rate (i.e. the number of resolvable spots scanned per second) achievable is $\frac{1}{2} \Delta f$, and the corresponding number of resolvable spots is $\frac{1}{2} \tau \Delta f$. This very high-speed light beam scanning has also been utilized for high-speed readout of the spectra of integrated optic RF spectrum analyzers.⁽¹¹⁾

On the experimental study, we have successfully carried out the guided-wave acoustooptic pulse compression experiment described above.⁽¹⁰⁾ This was the first successful demonstration of the technique. For this study we fabricated a very wideband deflector in a Y-cut LiNbO_3 Ti-diffused waveguide. This deflector employs a three-element tilted-array transducer⁽⁵⁾ with the center frequencies

of 275, 432 and 648 MHz, and has a measured deflector bandwidth of 500 MHz.⁽⁶⁾ This bandwidth represents the largest that has been achieved thus far. In our pulse compression experiment a linear FM pulse of 430 MHz center frequency and 120 MHz bandwidth was applied to the second transducer element of the array transducer referred to above (Fig. 3). A collimated and expanded light beam from a He-Ne laser at 6328 \AA wavelength was then Bragg-diffracted from the SAWs. Fig. 4 shows the RF pulse and the compressed optical pulse. A compressed optical pulse of 7 ns and a compression ratio of 200 was accomplished in this preliminary experiment.

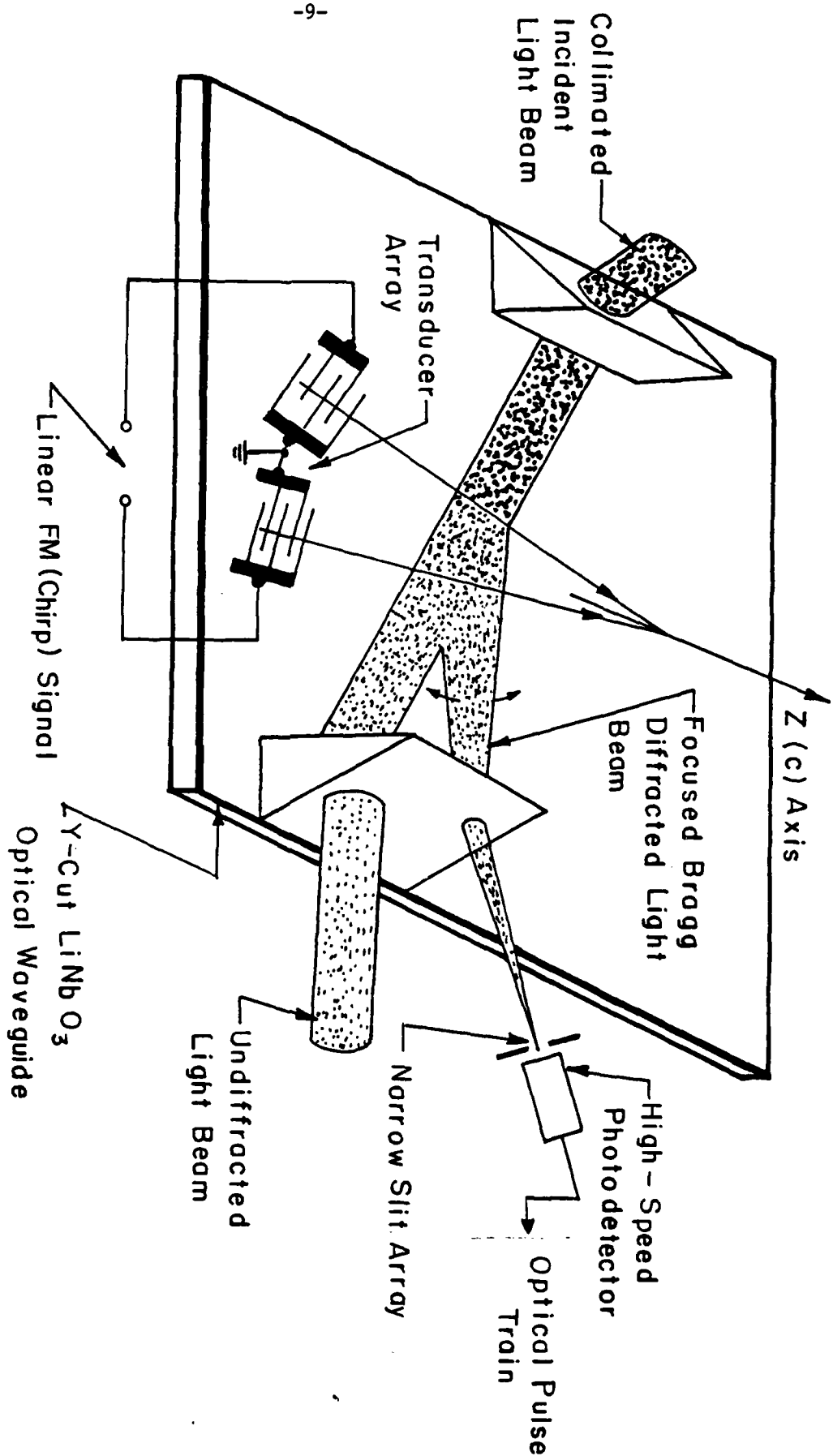
Using a fine slit of variable size we have accurately measured the width of the compressed optical pulse. We have also measured the location of the compressed optical beam (focal length) as a function of the aperture of the light beam and the frequency bandwidth of the linear FM drive signal. A good agreement between the measured values and the predicted ones has been achieved. During this effort the width of the compressed optical pulse has been reduced to 5 nsec (See Fig. 5) and the time-bandwidth product has been increased to 300. As a preliminary step toward achieving a larger time-bandwidth product some effort was also carried out to increase the bandwidth and the chirp rate of the linear FM drive. Further study toward this goal is in progress.

It should be noted that in a fully integrated AO pulse compressor all active and passive components may be formed in a single or small number of substrates. Such an integrated AO pulse compressor possesses many advantages over its bulk-wave counterpart. The guided-wave AO processors require less RF drive power. They are also smaller, lighter in weight, less susceptible to environmental effects, and more integratable, and thus potentially less costly.

IV. GUIDED-WAVE ACOUSTOOPTIC CONVOLVERS

A. Technical Discussion

The capability of performing real-time convolution between two rf signals is an important requirement in a radar system because of a great improvement in the signal-to-noise ratio which this technique provides. The time-bandwidth product of the signal processor is an important figure of merit indicative of overall system gain.⁽¹²⁾ Real-time convolution using bulk-type acoustooptic interaction configuration was studied by a number of workers in recent year.^(8,9,13) Investigation of a guided-wave interaction configuration has been suggested as a



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Fig. 3

EXPERIMENTAL ARRANGEMENT FOR GUIDED-WAVE ANALOG ACOUSTOOPTIC LIGHT BEAM SCANNING

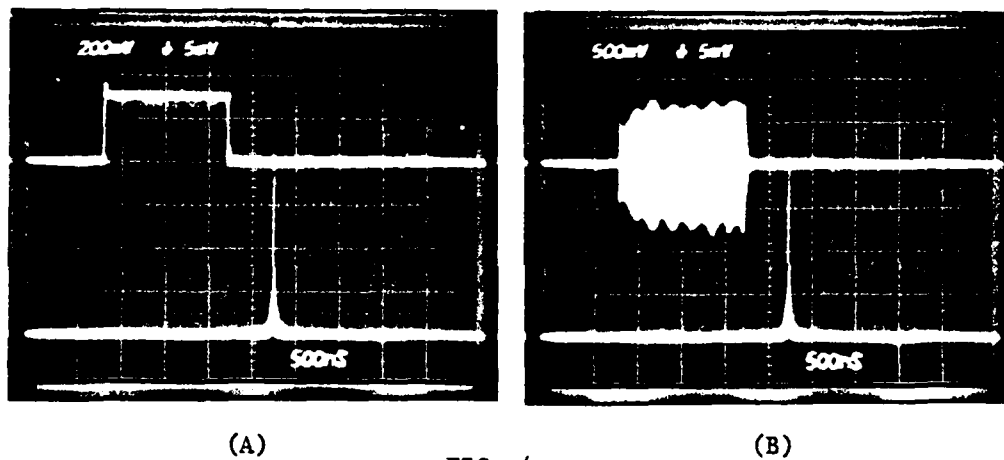


FIG. 4

OPTICAL PULSE COMPRESSION USING GUIDED-WAVE ACOUSTOOPTIC
BRAGG-DIFFRACTION AND RF CHIRP WAVEFORM

Modulating Pulse And RF Chirp Pulse (Upper Traces): 1.5 μ sec
Compressed Optical Pulse (Lower Traces): 7.5 nsec
Compression Ratio: 200

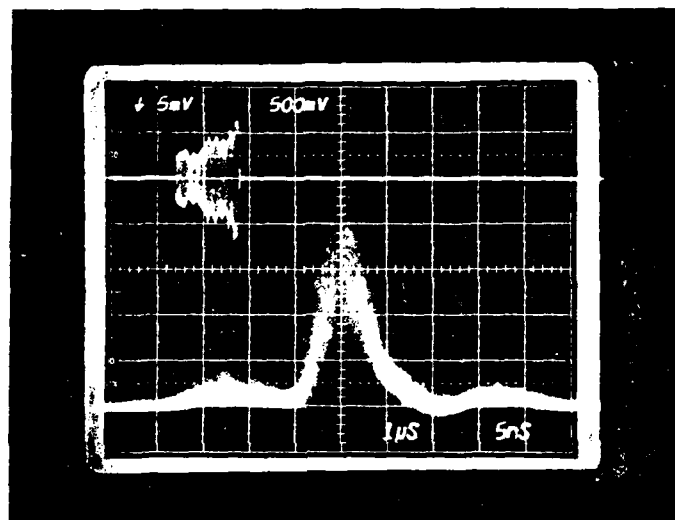


Fig. 5 WAVEFORM OF THE COMPRESSED OPTICAL PULSE

RF Chirp Pulse (Upper Trace): 1 μ sec per division

Compressed Optical Pulse (Lower Trace): 5 nsec
per division

result of the progress in the fabrication of both optical waveguides and surface acoustic wave (SAW) devices, and the fact that a more efficient interaction can occur in this configuration.⁽¹⁴⁾ We had earlier demonstrated this more efficient interaction with a guided-wave acoustooptic convolution experiment which employed out- and in-diffused Y-cut LiNbO_3 waveguides.⁽¹⁵⁾ This experiment demonstrated that multiple tilted SAW's described earlier can be employed to obtain very good performance figures for convolution with this guided-wave configuration. Multiple tilted SAW's have also been employed in a convolver without optical waveguide to achieve a large time-bandwidth product.⁽¹⁶⁾

The device configuration which we employed in the experimental study is shown in Fig. 6. An optical waveguiding layer of approximately 2 μm thick was first created on the top of a Y-cut LiNbO_3 substrate using in-diffusion technique. Two end-to-end identical SAW array transducers separated at a distance of 1.3 cm, which are characterized by staggered center frequencies (163, 194 and 230 MHz) and propagation axes tilted with respect to each other, were then deposited on the top of the waveguide. Each element transducer has an acoustic aperture of 3.2 mm and the tilt angles between adjacent element transducers are 1.25 and 1.50 mrad.

In the convolution experiment, one pulse-modulated rf signal (say, the reference signal) was applied to one array transducer to generate a SAW and the other pulse-modulated rf signal (the radar signal to be processed) was applied to the other array transducer to generate a second SAW propagating in the opposite direction. The two diffracted light beams overlap and were collected by a lens and then mixed in a P-i-n photodiode detector. The component in the electrical output from the photodetector which corresponds to the convolution of the two rf signals was further processed by means of a heterodyne receiver and then displayed in a wide-band oscilloscope. Typical waveforms of the convolution for single-pulse and double-pulse rf signals at the center frequency of 164 MHz are shown in Fig. 7(a) and 7(b), respectively.

The performance figures obtained include: a time-bandwidth product of 305 with a bandwidth of 107 MHz; a dynamic range of approximately 50 db at a total rf power of 310 mW for maximum convolution output; a frequency resolution of 1 MHz (defined at zero convolution output); and an optical through-put coupling efficiency of 18%. A considerably larger time bandwidth product can be achieved by increasing the center frequency of the acoustic wave and/or the aperture of the light beam. The 50 db dynamic range of the convolver was obtained at the input

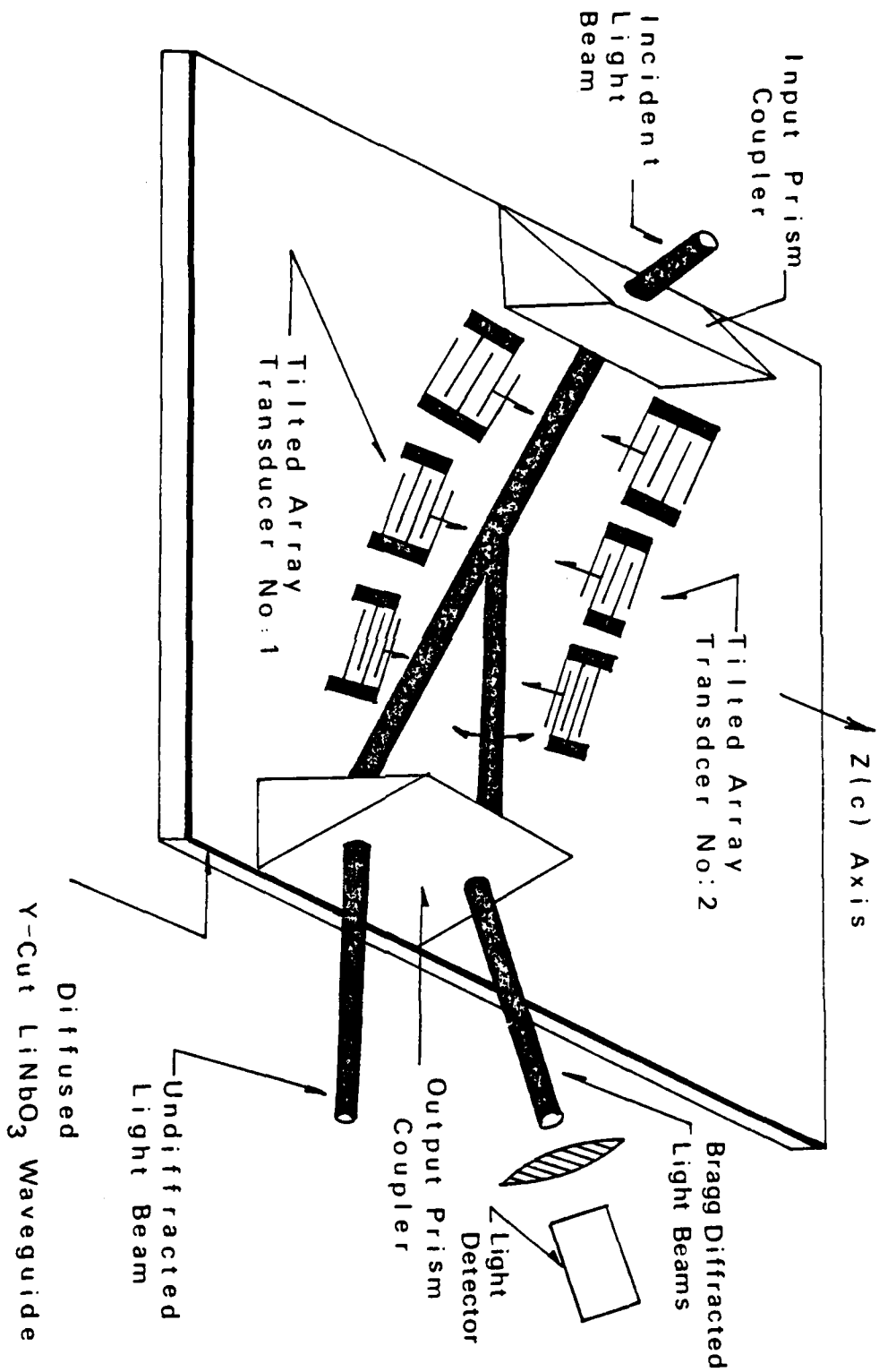


Fig. 6 Guided - Wave Acoustooptic Signal Processing Using Multiple Tilted Surface Acoustic Waves in LiNbO_3 Waveguide

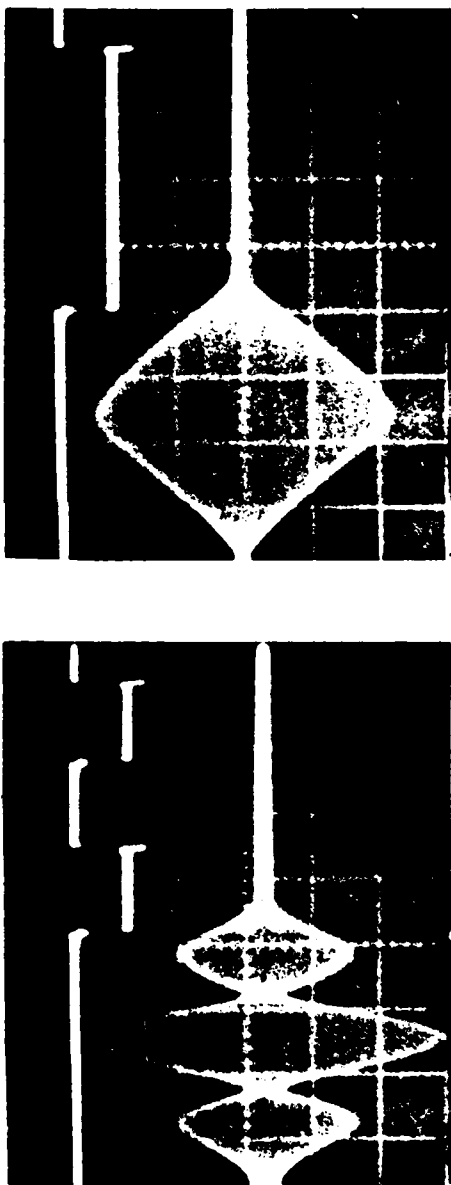


FIG. 7

Pulse-Modulated RF Signals (Lower Traces) and Their Corresponding Autoconvolution Outputs:

- (a) Single RF Pulse: Center Frequency (164MHz) , Vertical Scale (20mV/Div) , Horizontal Scale (0.5 μ s/Div.)
- (b) Double RF Pulses: Center Frequency (164 MHz) , Vertical Scale (10mV/Div) , Horizontal Scale (0.5 μ s/Div.)

light power (before being coupled into the waveguide) of 27 mW. The dynamic range can be greatly increased by using a larger light power and/or a more sensitive photodetector.

In summary, we note that better performance figures are achievable by optimizing the parameters of the convolver described above. We note also that the comparative advantages of such guided-wave acoustooptic convolvers over their bulk counterparts are:

1. More efficient diffraction, less RF drive power;
2. More flexible in the transducer design/fabrication, much easier for the implementation of multiple SAWs;
3. Smaller size, light weight; less critical with isolation and alignment problem;
4. Possibility for batch fabrication, less cost; and
5. Compatible with future integrated/fiber optic systems, suited for a number of wideband applications.

B. Major Accomplishments

A detailed theoretical study aiming at determining the ultimate performance figures of the acoustooptic convolvers such as bandwidth, time-bandwidth product, and dynamic range was initiated and being pursued. This theoretical study employs coupled-mode technique and is progressing at good speed. The findings of this study will be used to design a convolver of larger bandwidth and larger time-bandwidth product than the preliminary design described in the above technical discussion.

V. PERSONNEL

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VI. SCIENTIFIC PAPERS

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14. C.S. Tsai, "Wideband Guided-Wave Acoustooptic Bragg-Devices and Applications," Invited Paper, Proceedings of the 1975 Ultrasonic Symposium, IEEE Cat. 75CHO-994-4SU, pp. 120-125; C.S. Tsai, "Wideband Guided-Wave Acoustooptic Bragg Deflectors and Applications," Invited Paper, Proceedings of the Society of Photo-Optical Instrumentation Engineers, 90, Acousto-Optics, pp. 69-75 (1976).
15. I.W. Yao and C.S. Tsai, "Signal Processing Using Guided-Wave Acoustooptic Bragg-Diffraction in LiNbO_3 Waveguides," Proceedings of the 1976 International Microwave Symposium, pp. 21-23, IEEE Cat. No. 76CH1087-6MITT.
16. N.J. Berg and B.J. Udelson, "Large Time-Bandwidth Acoustooptic Convolver," 1976 Ultrasonics Symposium Proceedings, IEEE Cat. No. 76CH1120-5SU, pp. 183-188.